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Lead-free research activities and gaps for military and aerospace systems

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S.J. Meschter

BAE Systems

Johnson City, NY

stephan.j.meschter@baesystems.com

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14. ABSTRACT
The aerospace and defense electronics providers have a long history of adapting consumer and commercial electronic piece parts and assemblies for use in complex qualified systems. Driven by recent legislative directives, the consumer electronics industry has eliminated lead from its products. In comparison to the heritage tin-lead systems, the new lead-free material assemblies have introduced new failure modes that lack failure models and have different fatigue characteristics that are still being evaluated. As a result, design practices and qualification methods by which commercial-off-the-shelf items are introduced into high performance products are being re-examined. The aerospace and defense community is capturing pertinent research and technical guidelines from the military, aerospace and consumer electronics sectors in standards and handbooks to facilitate lead-free risk mitigation assessment in systems. However many shortfalls still exist, particularly in areas where consumer electronics performance regimes product complexity and sustainment requirements do not overlap with aerospace and defense systems. Some existing research as well as the Lead-free Manhattan Project Phase 2 report research proposal, formulated to close those technical knowledge gaps, will be discussed.

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LEAD-FREE RESEARCH ACTIVITIES AND GAPS FOR AEROSPACE AND DEFENSE SYSTEMS

DR. STEPHAN MESCHTER
BAE Systems
600 Main Street
Johnson City, NY 13760
(607) 770-2332
stephan.j.meschter@baesystems.com

The aerospace and defense electronics providers have a long history of adapting consumer and commercial electronic piece parts and assemblies for use in complex qualified systems. Driven by recent legislative directives, the consumer electronics industry has eliminated lead from its products. In comparison to the heritage tin-lead systems, the new lead-free material assemblies have introduced new failure modes that lack failure models and have different fatigue characteristics that are still being evaluated. As a result, design practices and qualification methods by which commercial-off-the-shelf items are introduced into high performance products are being re-examined. The aerospace and defense community is capturing pertinent research and technical guidelines from the military, aerospace and consumer electronics sectors in standards and handbooks to facilitate lead-free risk mitigation assessment in systems. However many shortfalls still exist, particularly in areas where consumer electronics performance regimes, product complexity and sustainment requirements do not overlap with aerospace and defense systems. Some existing research as well as the Lead-free Manhattan Project Phase 2 report research proposal, formulated to close those technical knowledge gaps, will be discussed.

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AIA-PERM Research coordination task team

- **The AIA-PERM Consortium was formed in response to aerospace and defense lead-free challenges**

  (AIA-PERM = Aerospace industries Association Pb-free Electronics Risk Management)

- **The *Research Coordination Task Team* is a major component of the activity**
  - Team is all volunteer and has no operating budget
    - Collects lead-free and tin whisker data through its world wide network of members
    - Keeps abreast of the various aerospace and defense research activities
    - Provides a sounding board for project ideas and vetting of research results for applicability to aerospace and defense

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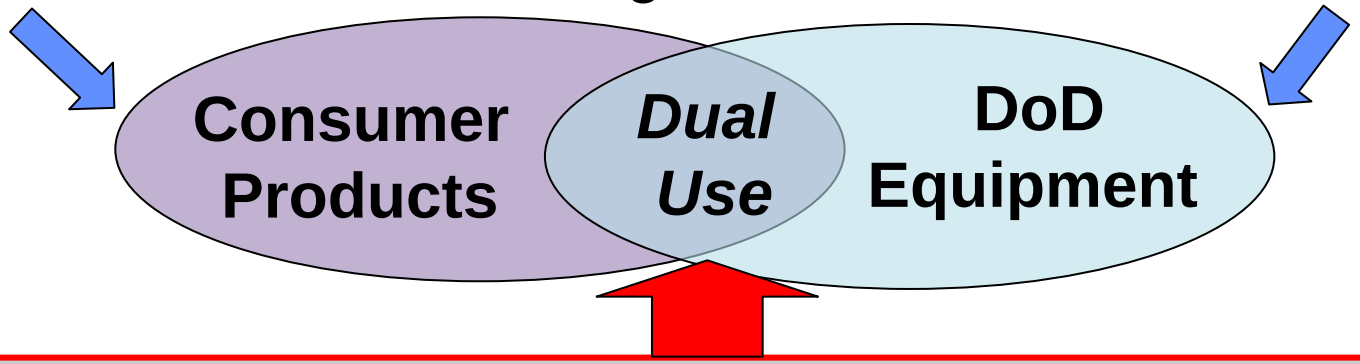
Basic challenge: DoD and commercial electronics

- ►1-2 Year Life, No repair
- ►Non-safety systems
- ►“Fractions of a cent” cost drivers
- ►RoHS compliant
- ►Rapidly changing
- ►High volume manufacturing

- ►Complex systems
- ►10-20+ year service
- ►High performance
- ►Critical safety items
- ►Rigorous qualification
- ►High mix low volume mfg



Consumer electronics supply base will not accommodate or solve DoD harsh operating environment reliability issues

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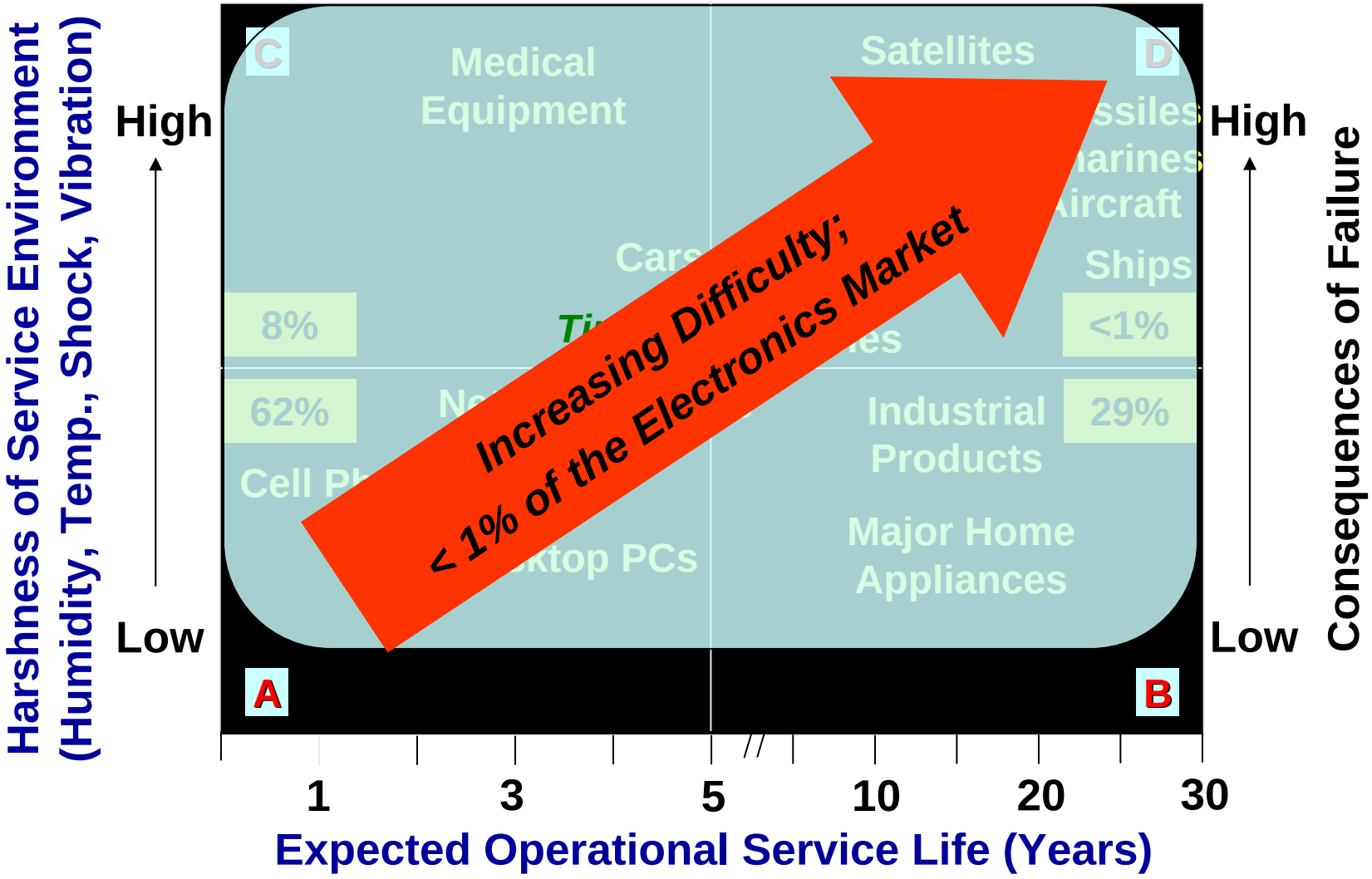
DoD Lead-free adaptation issue



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Commercial Electronics Research

- ***Effort started in 1995 to meet the 2006 European RoHS (reduction in hazardous substances) lead-free directives***
- ***Internet search queries***
  - *"RoHS" 28,100,000 hits*
  - "Lead-free solder" *1,160,000 hits,*
  - *"Tin whiskers" 92,000 hits*
- ***Major commercial electronics consortia***
  - *iNEMI international electronics manufacturing initiative*
  - *HDPUG High density packaging users group*
  - *SMART Group (Europe)*

Reliability gaps exist because the military is excluded from RoHS, but is dependent upon a supply stream that is lead-free.

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Published data

- **Significant volume of published literature on lead-free solder and tin whiskers**
  - From the DBI Corp. RoHS bibliography
    - References to 25 Directives and laws.
    - References to 260 books.
    - References to 223 Ph. D. and Master's theses.
    - References to 16,636 papers, magazine articles, and reports. (www.dbicorporation.com/rohsbib.htm)

Most publications relate to commercial electronics and may or may not be useful for Aerospace and Defense.

Aerospace and defense industry research consortia

- **CALCE, University of Maryland, College Park Maryland**
  - http://www.calce.umd.edu/general/center/consortium.htm
- **CAVE3, Auburn University, Auburn AL**
  - http://cave.auburn.edu/leadFree.cgi
- **Universal Instruments AREA, Binghamton, NY**
  - http://www4.uic.com/wcms/WCMS2.nsf/index/Global_Svc_Support_31.html
- **UK National Physical Laboratory Projects**
  - http://www.npl.co.uk/advanced-materials/materials-areas/electronics-interconnection/lead-free-soldering

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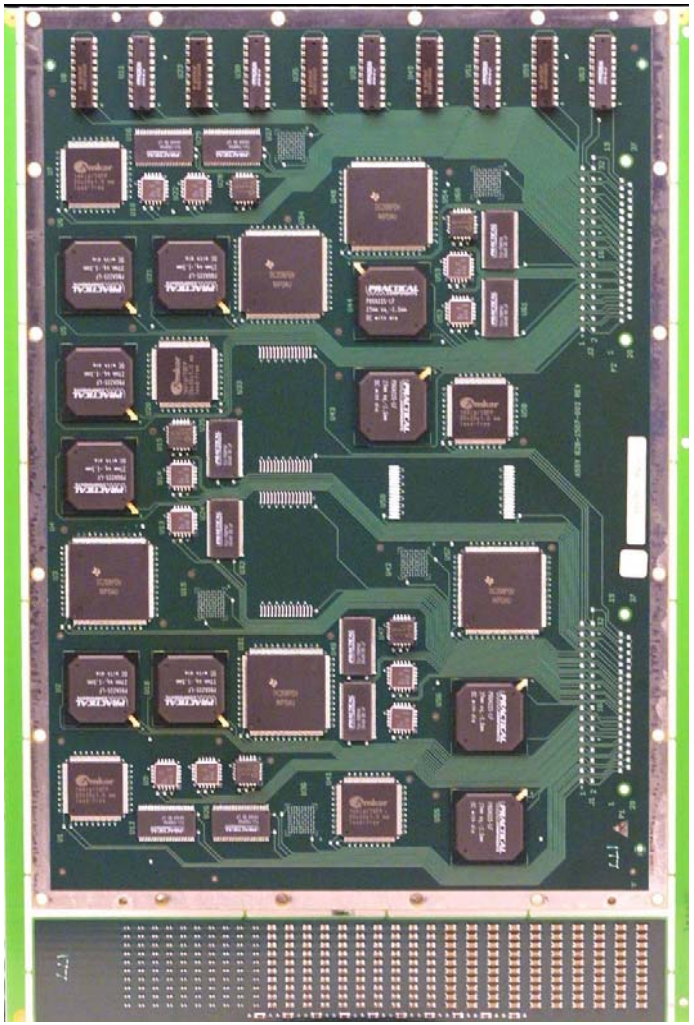
JCAA/JGPP 2004-2008

- NASA/DoD/Industry collaboration
- Aerospace and defense harsh environmental conditions
  - Combined thermal and vibration environment
  - Mechanical shock
  - Vibration
- Mature technology part types
  - Full part and assembly characterization for fatigue modeling



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JCAA/JGPP (continued)

- Evaluated “best” alloys at the time
- Various combinations of part finishes and solder
  - Mature through hole and surface mount parts
- 6 types of test vehicles fabricated
  - As-manufactured
  - Rework

Type	Circuit Card	Reflow Solder	Wave Solder
“Manufactured-Control”	T_g~170°C, GF, IPC-4101/26 Immersion Ag	SnPb	SnPb
“Manufactured-SAC”	T_g~170°C, GF, IPC-4101/26 Immersion Ag	SAC	SAC
“Manufactured-SACB”	T_g~170°C, GF, IPC-4101/26 Immersion Ag	SACB	SnCu
“Rework- Control”	T_g~140°C, GF, IPC-4101/21 SnPb HASL	SnPb	SnPb
“Rework- SAC”	T_g~140°C, GF, IPC-4101/21 SnPb HASL	SnPb	SnPb
“Rework- SACB”	T_g~140°C, GF, IPC-4101/21 SnPb HASL	SnPb	SnPb

Baseline alloy
•SnPb = 63Sn37Pb
Heritage tin-lead

Pb-free surface mount alloy:
•SAC=Sn3.9Ag0.6Cu
tin-silver-copper
• SACB=Sn3.4Ag1.0Cu3.3Bi
SAC with Bismuth

Through hole alloy:
•Sn3.9Ag0.6Cu
•Sn0.7Cu0.05Ni

http://www.teerm.nasa.gov/projects/LeadFreeSolderTestingForHighReliability_Proj1.html

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JCAA/JGPP (continued)

- **Sample results**
  - All results and test details are publically available
  - Study suggests that for some component types and environments, Pb-free solders are as reliable as the currently used eutectic SnPb solder.
  - However, it also demonstrates that with some component types and environments, the Pb-free solders fail before the SnPb control.

Under higher stress, SnPb performed better than Pb-free SAC alloys

SACB was best Pb-free

Relative Solder Performance N10 for "Manufactured" and "Hybrid" Test Vehicles Based on Two-Parameter Weibull Analysis

Component	Solder/Finish	Thermal Cycle -20 to +80°C	Thermal Cycle -55 to +125°C	CET	Thermal Shock
BGA-225	SnPb/SnPb	0	0	0	0
	SAC/SAC	P	++	--	NA
	SACB/SAC	P	++	--	NA
	SAC/SnPb	P	--	--	--
	SACB/SnPb	P	-	-	NA
CLCC-20	SnPb/SnPb	0	0	0	0
	SAC/SAC	++	--	--	--
	SACB/SACB	++	+	++	-
	SAC/SnPb	-	-	-	--
	SACB/SnPb	+	-	+	-

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JCAA/JGPP (continued)

- **Sample results**
  - The impact of SnPb contamination on the Pb-free solder alloy reliability is mixed.
  - For SAC, SnPb contamination can increase or decrease reliability.
  - For SACB solder alloy, SnPb contamination can have a detrimental effect on reliability.

Relative Solder Performance					
Component	Solder/Finish	Thermal Cycle -20°C to +80°C	Thermal Cycle -55°C to +125°C	CET	Thermal Shock
BGA-225	SnPb/SnPb	0	0	0	0
	SAC/SAC	P	++	--	NA
	SACB/SAC	P	++	--	NA
	SAC/SnPb	P	--	--	--
	SACB/SnPb	P	-	-	NA
CLCC-20	SnPb/SnPb	0	0	0	0
	SAC/SAC	++	--	--	--
	SACB/SACB	++	+	++	-
	SAC/SnPb	-	-	-	--
	SACB/SnPb	+	-	+	-
TQFP-144	SnPb/Sn	0	0	0	0
	SAC/Sn	P	--	-	NA
	SACB/Sn	P	++	0	NA
TSOP-50	SnPb/SnPb	0	0	0	0
	SAC/SnCu	++	--	--	NA
	SACB/SnCu	+	++	+	NA
	SAC/SnPb	+	--	-	NA
	SACB/SnPb	--	--	--	--

Unfortunately the best “as manufactured” alloy, SAC with Bismuth, is significantly degraded if mixed with SnPb rework solder. ***High risk*** for Aerospace and Defense repair.

NASA DoD 2007-present

- Even before all the results were in from the JCAA/JGPP test, the "***best***" Pb-free alloys had changed
- NASA DoD test is similar to JCAA/JGPP but
  - Evaluating new alloys
  - Some new packages

Baseline alloy
•SnPb = 63Sn37Pb
Heritage tin-lead

Pb-free surface mount alloy:
•SAC305=Sn3.0Ag0.5Cu
•SN100C=Sn0.7Cu0.05Ni+Ge

Through hole alloy:
•SN100C=Sn0.7Cu0.05Ni+Ge

http://www.teerm.nasa.gov/NASA_DODLeadFreeElectronics_Proj2.html

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NASA DoD 2007-present

- Results: Vibration
  - For some component types, the lead-free solders tested are not as reliable as eutectic SnPb solder with respect to vibration.
  - Rework also had a negative effect on both SnPb and lead-free solders with respect to vibration.
- Results: Mechanical Shock
  - Most of the components tested (including reworked components) successfully passed the tests defined in MIL-STD-810G 33 times each no matter which solder was used. These tests are:
    - Functional Test (Flight Equipment)
    - Functional Test (Ground Equipment)
    - Crash Hazard Test (Ground Equipment).
- Results: Thermal Cycling -55 to +125 °C
  - Completion of thermal cycling of test vehicles – 4068 cycles total
  - Failure analysis in process
- Other tests in process, e.g. -20 to +80 ° C
  - See Joint test protocol document

Each aerospace/military program will have to do their own qualification tests to determine if lead-free solders are appropriate for use in an electronic design on a specific platform.

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US SERDP

(Strategic Environmental Research and Development Program)

- 2010 four projects awarded

Thomas Woodrow	WP-1751	The Role of Trace Elements in Tin Whisker Growth
Peter Borgesen	WP-1752	Microstructurally Adaptive Constitutive Relations and Reliability Assessment
Stephan Meschter	WP-1753	Tin Whisker Testing and Modeling
Elizabeth Hoffman	WP-1754	Contributions of Stress and Oxidation on the Formation of Whiskers in Lead-Free Solders

- 2012 Solicitation under way
  - SON Number: WPSON-12-04
  - Reliability of tin-whisker-mitigating conformal coatings

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U.S. National facilities with lead-free activities

- **Sandia National Labs**
  - Solder properties modeling and fatigue assessment
  - Tin whisker work
- **Y12 National Security Complex**
  - Solder microstructure
  - Tin whiskers
- **Ames Labs**
  - Solder alloy development and intermetallic evaluation
- **NIST**
  - Database for lead-free solder properties
  - Tin whiskers

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NASA Tin Whisker (and Other Metal Whisker) Homepage

- **http://nepp.nasa.gov/WHISKER/**

Basic Info/FAQ **Other Metal Whiskers**

Literature References **Whisker Failures** **What's New**

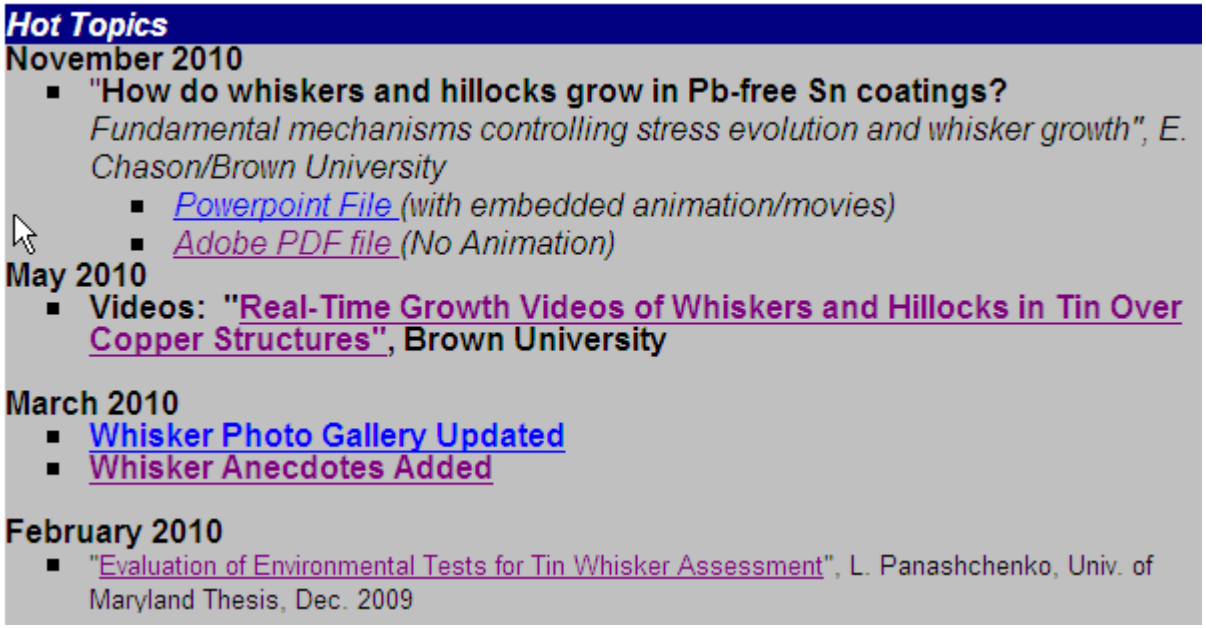
Whisker Anecdotes

GSFC Experiments

Photo Gallery

Video Gallery

Related Links



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U.S. SBIR/STTRs

- **SBIR: Small business innovation research**
- **STTR: Small business technology transfer**
- **16 SBIRs or STTRs for**
  - Lead-free reliability
  - Solder elimination
  - Tin whiskers
  - See appendix

http://www.dodsbir.net/awards/
http://www.science.doe.gov/SBIR/
http://www.dodsbir.net/selections/abs083/osdabs083.htm

Company Publications

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- **Many aerospace and defense companies/suppliers have published their lead-free research and tin whisker work**
  - Aerospace Corp
  - BAE Systems
  - Boeing Company
  - Celestica
  - Lockheed Martin
  - Rockwell Collins
  - European companies (See appendix)

Technical concurrence captured in

GEIA-HB-0005-2,

Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-free Solder and Finishes

(Government Electronics and Information Technology Association)

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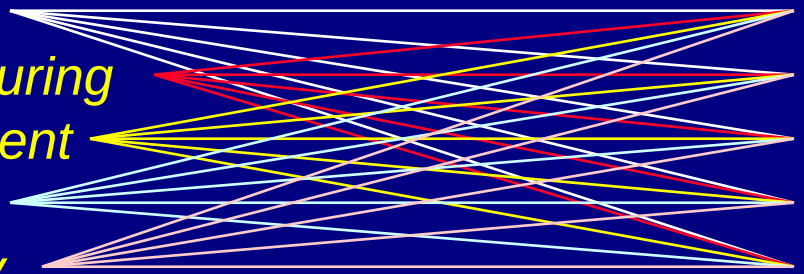
Lead-free Manhattan Project - 2009

- **Phase 1: Subject matter experts identified gaps associated with lead-free impact throughout the aerospace and defense product development, manufacturing and sustainment/repair.**
- **Phase 2: Specific projects were proposed for a Phase 3 program to close the lead-free technical research gaps.**

Phase 1 Baseline Practices & Knowledge Gaps

- *Design*
- *Manufacturing*
- *Sustainment*
- *Testing*
- *Reliability*



Phase 2 & 3 Risk Reduction Project Areas

- *Tin Whiskers*
- *Assembly*
- *Solder Joints*
- *Printed Circuit Boards*
- *Components*

(http://www.navyb2pcoe.org/b2p_news.html and https://acc.dau.mil/leadfree)

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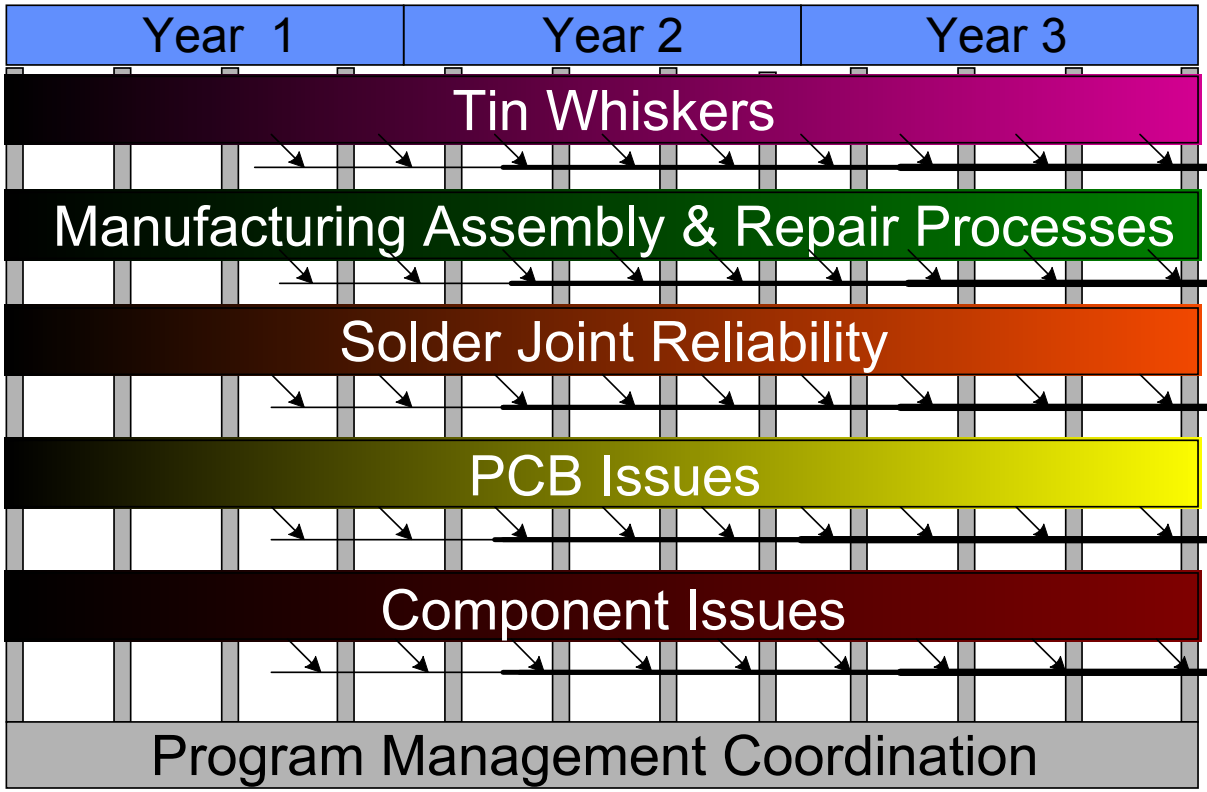
LFMP recommended roadmap



Tin Whisker Risk Mitigation

Interconnection Reliability

Pb-free Electronics Risk Reduction

KEY DELIVERABLES

- ***Detailed Design Guidelines for Use of Pb-free COTS Electronics***
- ***Validated Life-Prediction Models based on Physics of Failure***
- ***Methodologies for Assessing New Materials***
- ***Assembly and Repair Process Definitions***

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LFMP ROM Estimate

36-month Risk Reduction Program will enable continued use of COTS electronics in DoD products

WBS	Risk Reduction Project Area	ROM Cost in 2010 $ (M)			
		Year 1	Year 2	Year 3	TOTAL
A	Tin Whiskers	$ 6.3	$ 6.8	$ 6.5	$ 19.7
B	Assembly	$ 3.2	$ 4.0	$ 3.0	$ 10.2
C	Solder Joints	$ 13.9	$ 19.4	$ 13.3	$ 46.6
D	Components	$ 1.2	$ 2.6	$ 2.1	$ 5.9
E	Printed Circuit Boards (PCBs)	$ 3.9	$ 5.2	$ 3.5	$ 12.6
	TOTAL	$ 28.5	$ 38.0	$ 28.5	$ 95.0
	TOTAL with 10% Contract Administration Cost	$ 31.4	$ 41.8	$ 31.3	$ 104.5

Program Execution Budget Required in 2010 Dollars: $105M

Fundamental objective is to resolve knowledge gaps for use of Pb-free electronics as quickly as possible!

Conclusion

- **The AIA-PERM Research coordination team is tasked with collecting sources of lead-free data and activities pertinent to the aerospace and defense industry**
- **The JCAA/JGPP and the NASA DoD Lead-free reliability testing address some of the more significant facets of solder reliability, but….**
- **The Lead-free Manhattan project gap analysis illustrates the diverse and interconnected nature of the lead-free reliability issues and the need for coordinated focused research.**

- ***By the way:***

US Environmental Protection Agency study (2005):

- ***"Solders in Electronics: A Life-Cycle Assessment"***
- ***Compared 5 solder alloys:***
  - *tin/lead, tin/copper, tin/silver/copper,*
  - *bismuth/tin/silver, tin/silver/bismuth/copper*

Questions

- ***Measured impacts on:***
  - *Human toxicity & ecological toxicity*
  - *Landfills*
  - *Air and water resources consumed*
  - *Materials consumed*
  - *Energy consumed*
- ***Conclusion:***
  - *Switch to Pb-free solder is NOT beneficial overall*
- ***Reference:*** ***www.epa.gov/dfe/pubs/solder/lca/***

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Appendix

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SBIR/STTRs

Small business innovation research/Small business technology transfer

Principal Investigator	Citation/Description
Foresite, Inc./Purdue	Title: Tin Whisker Mitigation Technologies for Sn-based Surface Finishes on Electronic Assemblies and Microelectronic Devices
Applied Nanotech, Inc./ Univ. of Maryland	Title: Tin Whisker Mitigation by Photonic Sintering for Sn-based Surface Finishes
DfR Solutions	Title: Reliability Analysis and Prediction tool for Reballed BGAs in DoD Environments
Radiance Technologies Inc.	Title: Assessment of Reballing Methods for Ball Grid Array (BGA) Devices
DfR Solutions	Title: Development of Complex Shock and Vibration Model and Reliability Prediction Tool
GCAS Incorporated	Title: Assessment and Modeling of Shock and Vibration Performance of Lead-Free Alloys
QRDC, Inc. Texas Research Institute	Title: Performance Analysis System Software (PASS)
Austin, Inc.	Title: Assessment and Modeling of Shock and Vibration Performance of Lead-Free Alloys

SBIR/STTR (Continued)

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Principal Investigator	Citation/Description
SMITH & CO.	Title: Mitigating Lead-Free Issues in Electronic Circuit Board Manufacturing With an Advanced Conformal Coating to Manage Tin Whisker Risk
SUNDEW TECHNOLOGIES	Title: Mitigating Lead-Free Issues in Electronic Circuit Board Manufacturing and Repair
VISTA ENGINEERING & CONSULTING, LLC	Title: POSS-Based Conformal Coating with Active Tin Whisker Mitigation Properties
Faraday Technology, Inc.	Development of Tin Whisker Growth Model
Texas Research Institute Austin, Inc.	Development and Validation of Tin-Whisker Growth Model and Accelerated Testing
ECI Technology, Inc.	Development and Validation of Tin-Whisker

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US EPA Projects (Environmental Protection Agency)

Principal Investigator	Cross Reference	Citation/Description
Faraday Technology, Inc. Garich, Holly	EPA EPD09021	Enabling Commercialization of a Lead-Free Coating Manufacturing Process Project Period: February 1, 2009 through July 31, 2009
Georgia Tech Investigators: Wong, C. P.	EPA R831489	Fundamental Understanding and Performance Enhancement of Conductive Adhesive for Microelectronic Packaging Applications

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European aerospace and defense work

- **Green Electronics in Aeronautical and Military Communication Systems**
  - http://www.geamcos-euproject.com/
  - Poster : O. Maire « Forward Compatibility Assessment For Aeronautical and Military Communication Systems (GEAMCOS project) » EMPC 2007, Oulu (Finland), June 2007
  - Oral communication: O. Maire “Reliability of components with Pb soldered in a lead-free process” MicroNanoReliability 2007, Berlin, 3-5th September, 2007
  - Poster EADS IW Marc Grieu « Durability modelling of Ball Grid Array Components under random vibration » Symposium EuroSIME 2008 Freiburg (G) 21-23/04/2008
  - Communication ESTC (2nd Electronics System Integration Technology Conference) EADS IW Marc Grieu “Sn3.0Ag0.5Cu Solder Joints Lifetime Estimation for Electronic Assemblies under Random Vibration” Symposium ESTC 2008 Greenwich (GB) 01-04/09/08
  - EADS IW Agnès Chaillot: “Fatigue life prediction model developed for Green Electronics in Aeronautical and Military Communication Systems” Symposium EuroSIME 2009 Delft 28-30/04/2009